Chapter

New Generation Aero Combustor

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Abstract

The purpose of this study is to identify the technology for next generation aero combustors, and to propose totally new combustor design approaches. Next generation aero combustors need very high combustion air fraction, that brings idle lean blow out (LBO) problem. The present study suggests several measures to solve this problem, including: pilot and main two concentric combustion zones with separation, aerodynamic design to have main air slipping by pilot combustion zones, etc. For high fuel air ratio (FAR) combustor, the present authors propose using angled main fuel co-axial air plain jet injection. Make use of different penetration to meet the need for low power and high power conditions. For low emissions combustor, the present authors use small scale close contact fuel-air mixing with fuel staging to have low emissions at the same time to have good idle, good high altitude ignition, etc. Brand new cooling designs are proposed for outliner and inner liner. This chapter is mainly a survey of present author's own research. The results of this study will provide guideline for the development of next generation aero combustors.

Keywords: low emissions combustor, high FAR combustor, fuel air module design, liner cooling design, lean direct mixing combustion, idle LBO

1. Introduction

What are new generation aero combustors?

Aero gas turbine engine combustors have been developed over 80 years. It does not matter if it is a civil engine combustor, or military engine combustor. They are all developed under one line, that is, towards higher performance, higher reliability, and lower fuel consumption.

On 1977, International Civil Aviation Organization (ICAO) published a document named "Control of Aircraft Engine Emissions". Since then aero combustors have entered a new era, it is that of low emissions combustors. The requirements for low emissions are different for civil aero combustor versus military aero combustor. For civil aero combustors, their emissions are regulated by ICAO Committee on Aviation Environmental Protection (CEAP) [1]. The standard has been developed from CEAP 1, CEAP 2, CEAP 4, CEAP 6, now it is CEAP 8. It is getting more and more restrictive. Now-a-days, any civil aero engine thrust higher than 26.7 KN must be in accordance with the CEAP 8 standard. Their emissions of nitrous oxide (NOx), carbon monoxide (CO), unburnt hydrocarbon (UHC), and smoke shall all be controlled. Actually, an aero engine company is required to report the percentage their engine combustor will produce of each type of emission lower than the corresponding CEAP specified.

Because of the requirement of continuous improvement for reduction of fuel consumption, civil aero engines have development in two aspects. An aero engine as a propulsion unit has propulsion efficiency. This is to increase bypass ratio. On the other aspect, an aero engine is also a thermal engine, it has thermal efficiency. The way to improve its thermal efficiency is to increase the pressure ratio of the engine (at the same time, increase turbine inlet temperature appropriately). Thus, for several decades engine pressure ratio has been going up all the time, from nearly 10, then 20, 30, 40, 50, and pressure ratio 60 aero engines has been certified, will be in service soon. New generation civil aero engines will achieve a high pressure ratio of 70.

Conclusion: a new generation civil aero combustor is a high pressure low emissions combustor.

For a military aero engine, the most important development target is to have a higher thrust-to-weight ratio. In order to improve thrust-to-weight ratio, the engine shall have higher turbine inlet temperature (or higher combustor fuel air ratio, FAR) and increase the engine pressure ratio appropriately. Thus, the military aero combustor FAR has been increased from lower than 0.02 to 0.03, to 0.038, to 0.046. The new generation military aero combustor will have FAR, 0.051. Notice that a high FAR combustor is also called a high temperature rise combustor.

Conclusion: new generation military aero combustor is high FAR combustor.

2. Design of high FAR combustor

For a military aero combustor, there is no 30% power condition, no 85% power condition, and no maximum cruise condition. There is a ground idle condition, maximum power condition (or 100% power condition) and cruise conditions at different altitudes and different Mach numbers. There is a high altitude idle condition. Particularly there is low altitude not-so-low Mach number penetration dash condition. In this condition, the combustor inlet pressure may be even higher than at the take-off condition. The inlet air temperature is very close to the take-off condition and FAR is only a little lower than take-off condition. At this condition, liner wall temperature higher than that at take-off condition is possible.

Don Bahr [2] reported that there are two major problems for high temperature rise combustor design; they are idle lean blow out (LBO) and liner cooling. According to present author's experience, it is true that these two issues are critical for high FAR combustor design and development. But there are other issues too. The design reported in this chapter is mainly from reference [3].

2.1 Idle LBO

For military aero combustor idle LBO issues, the present author proposed several design approaches. One approach is that, there is a concentric "twin" combustion zone concept. That is, the pilot fuel air combustion zone is at the center, main fuel air combustion zone is surrounding the pilot fuel air combustion zone, with some separation. Significantly, a reduction of the main air quenching effect on pilot fuel air combustion is performed. This is the way to improve idle LBO. The annular combustor has several fuel air modules, the fuel air module configuration is shown in **Figure 1**. This multiple swirler dome design is very different from reference [4]. The pilot fuel air module consists of a pressure swirl fuel nozzle and an axial air swirler. The main air module has a distance radially away from pilot module. This distance is from pilot module exit diameter to the inner diameter of main module annular exit. In this design it is 0.95 in.

The second design approach for solving idle LBO issue is the combustion zone aerodynamics. As shown in **Figure 1**, the main air module consists of two portions, one third is non-swirling air on inner side and two thirds is swirling air. The pilot module air is having weak swirling. Together with the separation distance, the combustion zone aerodynamics is shown in **Figure 2**. The combustion aerodynamics is low swirling. But in the present design, there is combination of swirling air and non-swirling air, which is rather different from reference [5]. The key feature is that the main air flow is just slipping and passing through pilot air recirculation without mixing with pilot air, that is the most important factor for reducing main air quenching effect on idle condition pilot fuel air combustion.

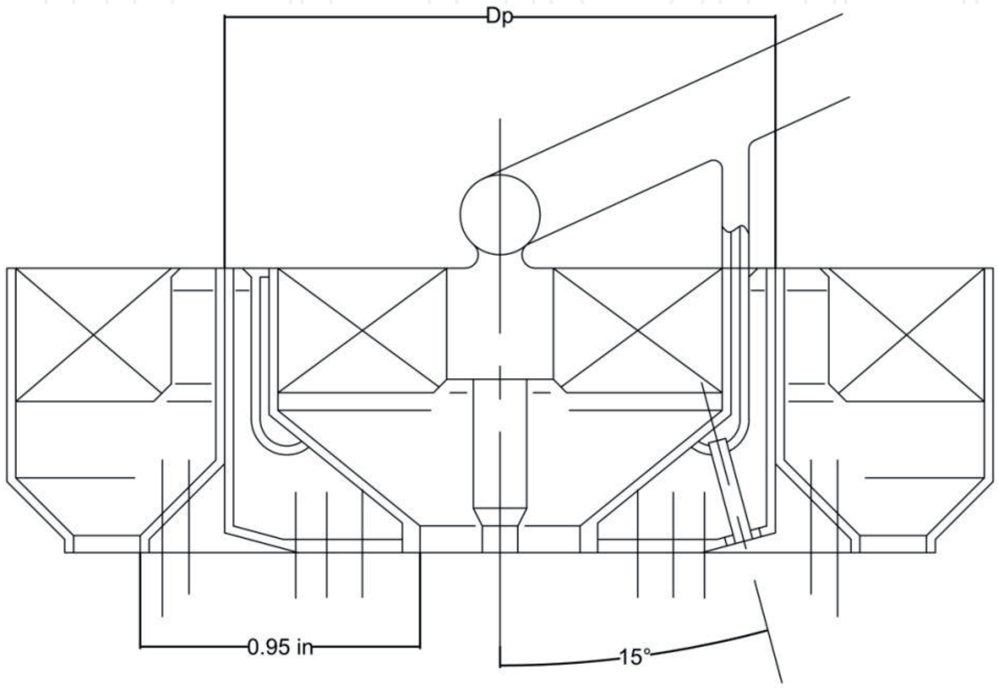

Figure 1.
Fuel-air module [3].

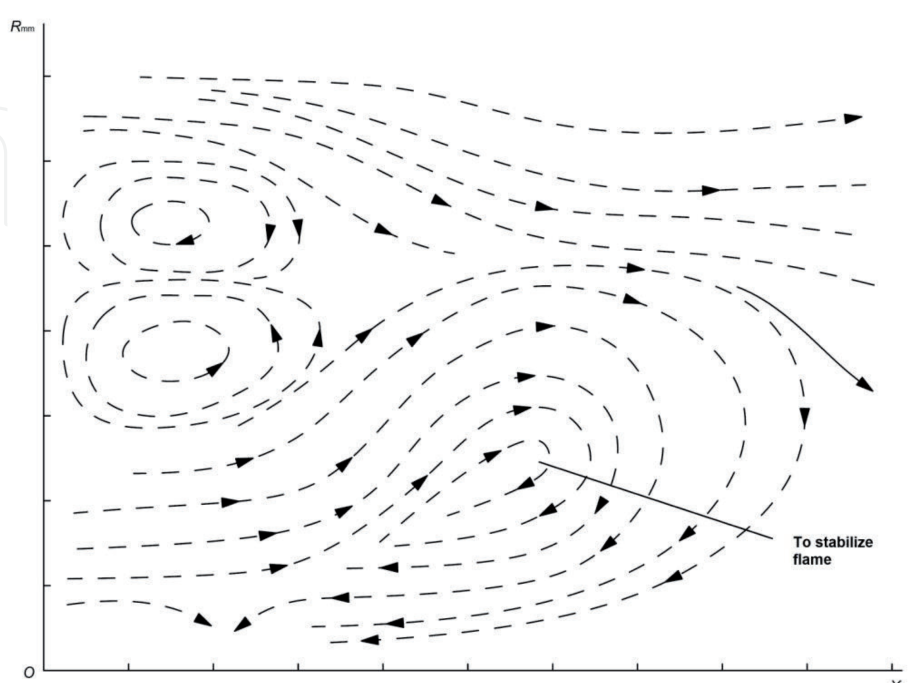

Figure 2.
Air flow pattern [3].

The third design approach for solving idle LBO issue is design of pilot fuel air combustion. Pilot fuel air combustion, pilot air alone module and pilot fuel nozzle are designed at idle condition, not at maximum condition. For high FAR combustor, its idle condition FAR is higher than idle FAR for civil combustor. At the idle condition, if only the pilot fuel is working, when approaching flame out, the pilot fuel nozzle pressure drop will be very low, which is harmful for LBO (it is not practical that at idle condition pilot fuel nozzle pressure drop is extremely high, such as higher than 200 psig). Thus, it needs main fuel to be open to work together with pilot fuel combustion. At the idle condition, its fuel flow is split at 70% pilot fuel and 30% main fuel. 70% idle fuel flow together with pilot module air to form an idle pilot fuel combustion at equivalence ratio 1.2 and based on this design criteria to determine pilot air fraction within the combustion air. At idle condition, 30% main fuel with co-flowing air to provide idle main fuel combustion equivalence ratio 1.2 to determine co-flowing air amount. At idle condition, the main fuel injection pressure drop is very low, main fuel jet spray with co-flowing air is collapsed with pilot fuel combustion. Pilot fuel nozzle operation is designed at idle. At idle condition pilot fuel nozzle pressure drop is 120 psig. Based on this design approach to determine pilot fuel nozzle flow number (FN). There is a flow divider valve between the pilot fuel nozzle and the main fuel injector. The crack pressure for this flow divider valve is a critical design parameter. It needs to have an initial choice, then after both pilot fuel and main fuel design finished for the whole power condition range, it may be modified several times. Pilot fuel nozzle spray angle is 90 degree. The pilot air module inlet swirler is a thin curved blade low swirling axial swirler. The inlet effective flow area (ACd) is much higher than exit ACd to let the exit be the flow metering device.

High FAR combustor idle LBO design is related to many aspects. There are several design choices which must be balanced, making many times modification to have an all-round good solution. These design choices are:

- Idle condition, main fuel-pilot fuel division

- Idle condition, pilot fuel combustion equivalence ratio (determine pilot combustion air fraction).

- Idle condition main fuel and coaxial flowing air FAR ratio (determine co-flowing air amount)

- Idle condition, pilot fuel nozzle pressure drops (determine pilot nozzle flow number)

- Idle condition, main fuel injection pressure drops

- Flow divider valve crack pressure (affect at maximum condition, difference of injection pressure drop between pilot nozzle and main fuel injector, affect required maximum pump pressure capability)

- Maximum condition pilot fuel and main fuel division (determine maximum condition pilot fuel combustion and main fuel combustion equivalence ratio)

The final design shall have good idle LBO, appropriate maximum condition pilot fuel and main fuel combustion equivalence ratio (none of them may exceed 1.2), and a maximum fuel nozzle pressure drop which is not higher than 800 psig.

Conclusion: with these design measures, a high FAR combustor idle LBO problem is solved [3].

2.2 Design of maximum condition

Design of maximum condition is to reach both pilot fuel and main fuel combustion near stoichiometric combustion to determine the total combustion air fraction [3]. For example, if the combustor FAR is 0.051, combustion air is 75% to have combustion FAR 0.051/0.75 = 0.068, which is an equivalence ratio of one. Then the main fuel combustion air fraction is total combustion air minus the pilot combustion air fraction.

Main fuel air combustion design is concentrated on main fuel injection. As shown in **Figure 1**, main fuel is co-axial air flowing plain jet fuel injection. There is an angle, between main injection center line and module center line, which is 15 degree in this design. This injection angle is a critical design choice. At the low power condition, main fuel injection pressure drop is very low, main fuel will not penetrate far away, thus main fuel will burn with pilot fuel combustion. At maximum power condition, main fuel injection pressure drop is very high, the spray will penetrate radially out to meet main air to form direct mixing combustion. Here the **design idea is to make use of the change of penetration to suit low power condition and high-power condition** [3]. That is the reason why the main fuel injection must be with an angle relative to module center line. Main fuel injection pressure drop at maximum condition is very high, hopefully higher than 600 psig. Somewhere between 40% to 60% power condition, there will be a situation the main fuel spray will detach from the pilot fuel combustion to form a separate main fuel air combustion zone. Main fuel penetration and mixing with main air is critical to form non-visible smoke, to have non-luminous flame, to have high efficiency at maximum power condition. Because of the need for high penetration, the main fuel injector is not a hole, but a **section of straight tubing of diameter 0.03 in**. Notice that the present author does not call main fuel injection as co-axial air blast atomization, but rather air co-flowing plain jet injection. In studies on such injection, it was found that under very low liquid injection pressure drop, it is air blast atomization, at medium injection pressure drop, it is air assist atomization, with very high liquid injection pressure drop, it is air retard atomization. Air retard atomization is a new term. It is a case where air does not help atomization of a finer drop size, but hurts atomization by becoming a coarser drop size. Actually, this is good. This is because with very fine droplets, the spray cannot penetrate far out, while for main fuel combustion, at high power condition, penetration is more important than drop size. But it is not the more penetration the better, for fuel injection the present author shall take atomization, penetration, dispersion and fuel air mixing all four aspects into consideration.

Notice that the circumferential distribution of main fuel injectors may be uniform or may be non-uniform. For example, main fuel injector positioning may start other than 12 o'clock position. The different main fuel injector circumferential arrangement is for minor adjustment of exit radial temperature and FAR profile because there is no dilution air.

3. Other issues

3.1 Combustion efficiency

High FAR combustor has a combustion efficiency issue. Some designer mentioned that for high FAR combustor, at maximum power condition, its efficiency can only be 98%, it is because of chemical dissociation. The present author has studied chemical dissociation. It will have significant effect on efficiency at higher temperature. For aviation kerosene and air combustion, at stoichiometric fuel air ratio, the effect of chemical dissociation will not be so much. Thus, for well-organized high FAR combustion, its combustion efficiency shall be higher than 98%.

3.2 Exit distribution

Notice here the title is only exit distribution, not exit temperature distribution. In reference [6], it was reported that for high FAR combustor exit temperature radial profile is different from exit FAR radial profile, as shown in **Figure 3**.

If **Figure 3** is a true situation in the engine, that is very harmful. This is because the over rich combustion gas entering turbine, meeting with turbine cooling air, will result in additional burning which can totally destroy local turbine cooling. But this was some work done more than 20 years ago. At that time the combustion organization for high FAR combustor was poor. Combustion was rather non-uniform. From present design, the high FAR combustion is well organized, there will not be such severe difference. The temperature defined radial profile and FAR defined radial profile will be of same shape. But the point reported in reference [6] is very important. It shows that to delete some extremely rich pockets in the combustor exit is of very high importance. It also shows in addition to temperature defined exit radial profile, there shall be FAR defined exit radial profile.

3.3 Visible smoke

High FAR combustor must avoid visible smoke. This requirement is not only for the maximum condition, it is for all operational conditions. For smoke reduction, fuel additives method cannot be used [7]. To avoid maximum condition visible smoke, design at maximum condition combustion fuel air ratio is stoichiometric, particularly pilot fuel combustion shall not be over rich, avoid any possible local over rich pocket, and the whole combustion FAR shall be uniform. In reference [2], Don Bahr reported the number one issue for high temperature rise combustors is the contradiction between high power condition visible smoke and idle LBO. As mentioned in this chapter, if the idle LBO problem is to be solved, then the design may significantly increase combustion air fraction, such as for combustor FAR 0.051, combustion air is 75%. Then **the combustor cannot have primary air**

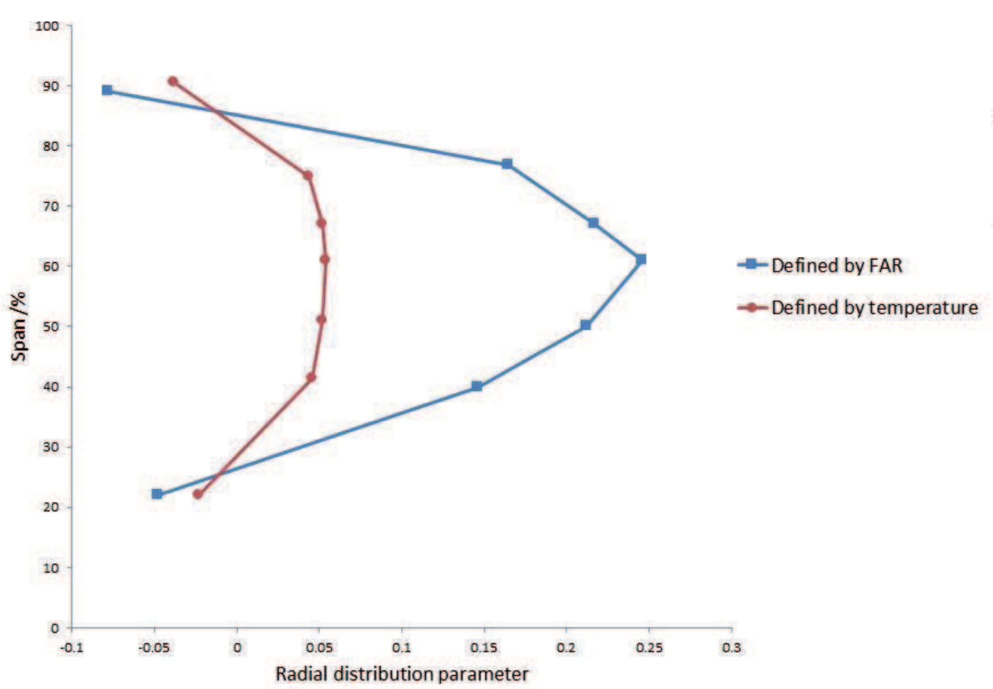

Figure 3.
Difference between temperature defined and FAR defined radial distribution parameter [6].

holes. Also, there is no dilution air holes. That brings liner configuration greatly changed. Also needs to use other design measures to have exit distribution adjusted.

3.4 High altitude ignition

As combustion air fraction is significantly increased, there is a high altitude ignition issue. For a high FAR combustor, it is required to have 35000 ft reliable ignition. It is more severe than civil aero combustor requirement, which usually has a 30000 ft ignition. Also, it is not only required to have ignition, it must provide engine with quick pull-up. That is after high altitude ignition, the combustion efficiency must be appropriately good for pull-up.

Two major design measures for high altitude ignition are:

a. Enlarge the liner cross sectional area. Liner cross sectional area is, **at least** equal to 12 times combustion air ACd

b. Using small FN pilot fuel nozzle. That is the reason why at idle condition pilot fuel nozzle injection pressure drop at least 120 psig

3.5 NO_2 issue

A high FAR combustor has a special issue, that is exhaust nitrogen dioxide (NO_2). This is an environmental issue, NO_2 is toxic. When NO_2 exhausted to atmosphere it will combine with water vapor to form nitrous acid (HNO_2) and nitric acid (HNO3), they are volatile micro matter. But for military combustor, it is related to visible exhaust.

NO_2 is a brown color gas, at 50 ppm volume concentration, it is visible. It has been seen in previous aero engine operation with afterburner working. Thus, the design requirement is that combustor exhaust raw NO_2 concentration lower than 50 ppm (not converted to 15% oxygen concentration). In combustor, chemical reaction mainly generates NO, but under some conditions NO will be converted to NO_2. Chemical reaction NO plus HO2 will become NO_2 plus OH. That will be the case when high temperature combustion gas meets cold air temperature 1100 degree F. Particularly if in combustor there is some UHC, UHC will accelerate the NO_2 formation reaction. Notice that if soot particle combined with NO_2 their visible concentration limit will be lower than when each of them counting separately.
To control NO_2 from a high FAR combustor, the combustor designer needs to do three things:

- Manage to reduce the total NOx level [8]. This is very difficult. At stoichiometric combustion, NOx is at 1000 ppm level. Even with rather low NO_2 over NOx ratio, which is about 8%, NO_2 is at 80 ppm level

- Avoid direct contact between high temperature combustion gas with cold cooling air

- Try to reduce UHC

3.6 Cooling

Reference [9] is important for liner cooling. The author reported it is not right try to make use of air flow passing through liner wall material absorbing heat to solve liner cooling issues, which was the way Lamilloy developer used.

For high FAR combustor, liner cooling is another very big issue. The present author cooling design is effusion cooling with brand new cooling hole configuration. Experiments have proven they are much more effective than conventional cooling configuration.

3.6.1 Outer liner cooling

The outer liner cooling configuration is shown in **Figure 4** [3]. The same configuration may also be used for tubular combustor. It is a tangential hole, but **not totally tangential,** it is **a compound angle tangential hole**. As shown in **Figure 5**, the axial direction angle is to prevent the upstream air jets impinging the downstream cooling air jets. 15 degree angle is only an example. The designed axial direction angle shall be based on axial spacing and circumferential spacing. It is Arctan (H/3*S), as shown in **Figure 5**. From cooling hole center line to the wall inner surface there is a short distance. The minimum distance is half hole diameter. Of course, if the hole is perfectly tangential to the inner wall that is the best. Because it will be the most compact air flow. Depending on liner wall manufacturing, this distance may be more than half hole diameter. For a machined tubular liner, it is half the hole diameter plus 0.005 in. For a large diameter liner formed by sheet metal rolled and welded, this distance may be half hole diameter plus 0.02 in, depending on the liner roundness to avoid laser drilling blind hole.

Such cooling configuration design is based on the present author's long-time cooling study. The most important concept for liner cooling is not how to have cooling air passing liner wall internal passage absorbing more heat, such as Lamilloy (or Transply). That is no good. It is **how to form a compact cooling air layer sticking on wall surface**. The present author's cooling design is based on such concept. The compound angle tangential cooling hole will form such a thin, compact air layer

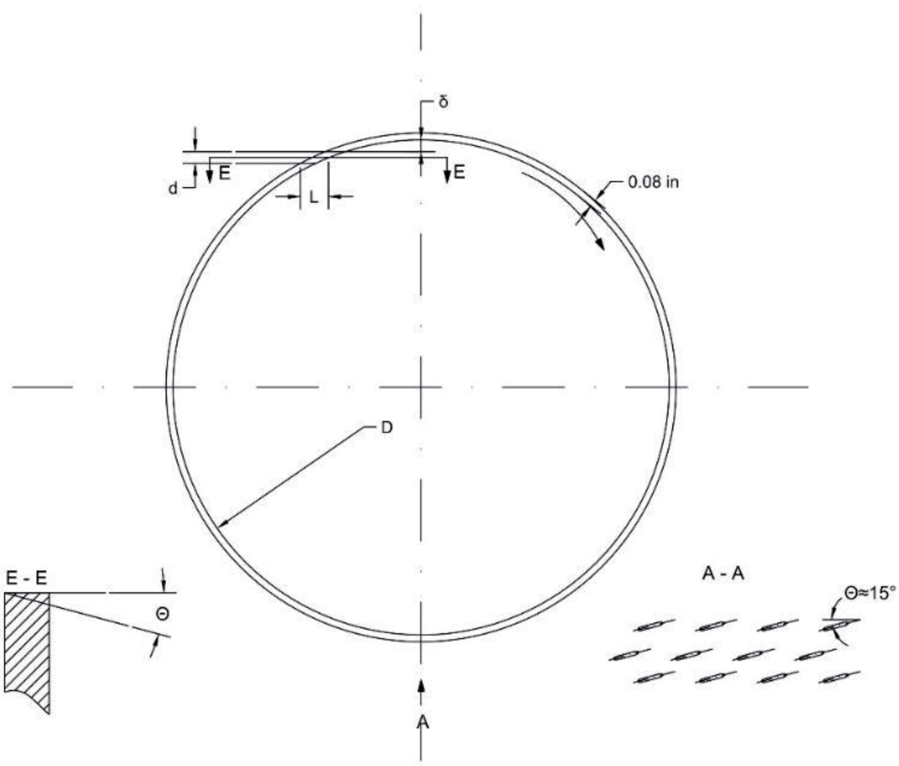

Figure 4.
Cooling hole configuration for annular or tubular liner [3].

sticking on wall surface, to **force the convective heat transfer from hot wall to the lower temperature cooling air layer**, **instead of from gas to wall.**

Of course, the longer cooling hole length is helpful for liner cooling. As shown in **Figure 6**, by author's own calculation, if liner diameter 25 in, cooling hole diameter 0.02 in, hole center line to inner wall surface is 0.03 in, cooling hole length, as defined by the hole center line length, is 0.8 in. This is good for liner cooing. It shall be stressed that the major advantage of this cooling design is not the long hole length. Instead, it is the cooling effectiveness. For a properly designed and manufactured cooling hole arrangement, very often the cooling effectiveness is 100%. From video an **air layer is spirally flowing around the liner surface**. That is why the cooling effectiveness is very good. The major weakness of Lamilloy is not its air passage inside of liner material is too short, it is the hole exit flow vertical to the wall surface, there will be more mixing of cooling air with the combustion gas, thus cooling effectiveness is low.

For outer liner or tubular liner compound angle tangential cooling hole the discharge coefficient can be 0.86. The discharge coefficient depends on laser drilling. If the laser drilled hole likes something "dog bite", then the discharge coefficient will be lower. If laser drilling technology is available for even smaller holes, it is desirable to have smaller hole but more number of holes.

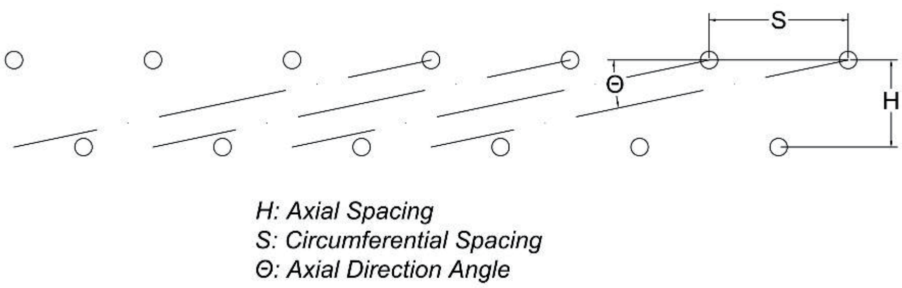

Figure 5.
Design of the axial direction angle in compound angle tangential inlet cooling hole configuration [3].

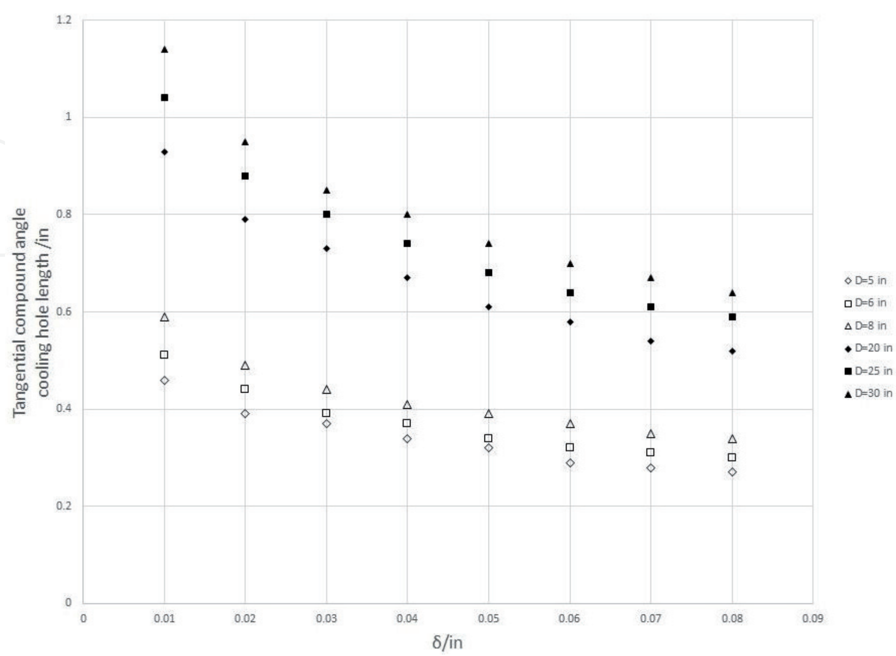

Figure 6.
Tangential compound angle cooling hole length changed with the distance from hole centerline to liner inner surface for tubular and outer annular liner, hole diameter 0.02".

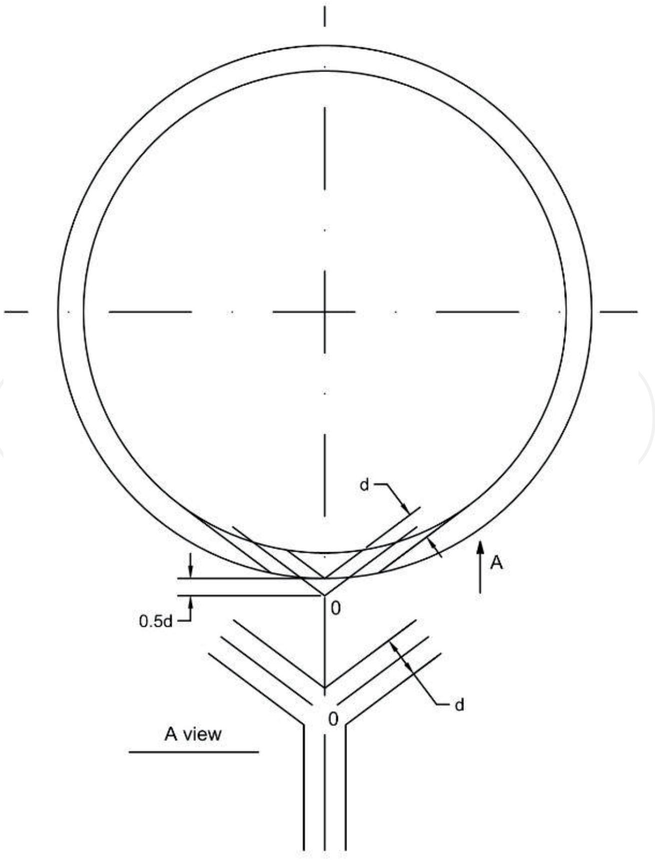

Figure 7.
Cooling hole configuration for inner liner [3].

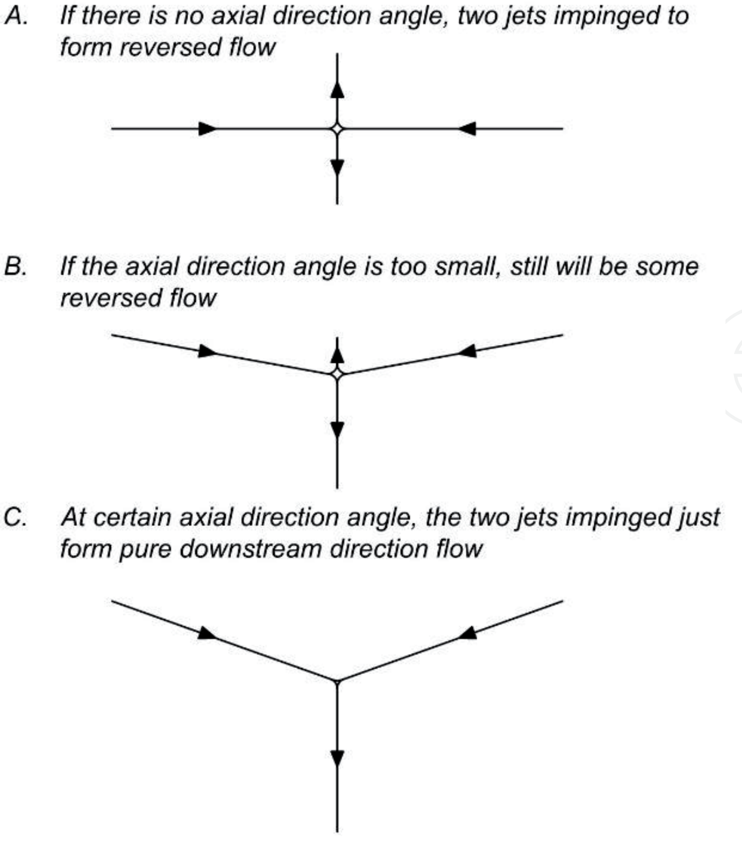

Figure 8.
For inner liner cooling hole, there must be axial direction angle [3].

3.6.2 Inner liner cooling

Inner liner cooling is very different from outer liner cooling. Because if using the same configuration, the cooling air will flow away from the wall surface to mix with combustion gas, which is very bad for cooling result.

Inner liner cooling configuration design is based on one concept that **two compound angle tangential flowing air jets impinged at wall surface to form a pure axial direction cooling air layer**. The design is shown in **Figure 7** [3]. The impinged two jets must have axial direction angle. As shown in **Figure 8** this axial direction angle must be larger than a certain value to avoid the impinged jets forming reversed flow. The minimum axial direction angle depends on liner diameter. Of course, no need to have axial direction angle greater than the necessary one.

In a conventional combustor there are machined cooling air rings, which has one advantage, which is that the cooling air is flowing in the axial direction. However, the machined ring has a lip, which is life limiting factor. Now the newly designed inner liner cooling configuration has truly axial direction flow cooling air, but without a life limiting factor.

Such inner liner cooling configuration is very good. But it brings some challenges to laser drilling. Particularly drilling very small holes.

Such cooling designs are suitable for high FAR combustor, suitable for low emissions combustor, actually suitable for all kind gas turbine combustors.

4. High pressure low emissions combustor design

For a very high pressure civil aero combustor, it cannot use lean pre-vaporized-premixed (LPP) combustion. Because for an engine of pressure ratio 70, its combustor inlet conditions (inlet temperature and inlet pressure) are so high that the autoignition delay time is extremely short, that will not provide any useful reduction of NOx, but suffer very high risk of auto-ignition. From reference [10], auto-ignition delay time for aviation fuel at high pressure and high inlet temperature were obtained (pressure at 40 atm, temperature at 900 K, not so high as up to pressure ratio 70). The present author derived a calculation model, the pre-ignition chemical reaction and heat release were correlated by fitting the prediction to the experimental data. Then using the model to predict auto-ignition delay time for pressure 70 engine combustor inlet condition. The delay time is 0.31 msec. With a safety factor of 2, the usable premixing time is 0.155 msec. That is really no meaning to design an LPP combustion. Thus, it can only be non-premixing combustion. But for low NOx, at high power condition, fuel and air shall still be well mixed. Then it must be **direct mixing combustion**. Actually, for a high FAR combustor, it is also direct mixing combustion. The difference between these two direct mixing combustions is that, for a low emissions combustor, it is **lean direct mixing (LDM) combustion**, for high FAR combustor, it is **stoichiometric direct mixing combustion**.

4.1 LDM vs. LDI

More than 20 years ago, someone suggested using lean direct injection (LDI) combustion. The suggestion was very simple, only a sketch. Actually, direct fuel injection was not a new concept. All conventional aero combustors (except vaporizer combustor) have fuel direct injection. There was no explanation from LDI suggestion, how to design a combustor for low emissions. Later on, several fuel air module configurations were proposed and tested. Unfortunately, the emissions were no good. Even more trouble is the fact that these fuel air module configurations cannot be integrated on to engine combustor.

Present author proposed lean direct mixing concept. The concept has put stress on one thing that the major design approach shall be concentrated on how to improve high power condition fuel air direct mixing. And the fuel air module proposed by the present author, is based on basic mixing concept, with realistically mechanical design, it can truly be integrated on to engine combustor.

Conclusion: for high pressure low emissions combustor, it is LDM, not LDI.

4.2 Mixing concept

For good fuel air mixing, fuel and air shall have close contact. There must be small scale mixing. Thus, the fuel air module shall be of small size. From many years combustion research, combustor design and development, combustor test, the present author has defined **one very good and simple small size fuel air module**. It is one **single axial flow air swirler, and in the center position**, there is a simple pressure swirl fuel **nozzle**. Such combination will offer good efficiency and flame stabilization at low conditions (such as idle condition) with near stoichiometric combustion, while at high power condition, it is very close to premixing situation, if it is lean burn, it offers low emission index (EI) of NOx. There is a fundamental reason. At a high power condition, fuel injection pressure is high, atomization spray drop size is fine, with high air temperature, fuel evaporation is rather quick. Then with appropriate air swirling, fuel air mixing is good**. The flame zone cannot distinguish if it as a pre-vaporized, premixed fuel air mixture in a premixed module, or if it is mixed out of module during the flowing process before reaching the flame zone**. For combustion these two cases do not have a significant difference. That is the reason why at a high power condition, with high pressure, such small size one single axial air swirler plus one simple pressure swirl fuel nozzle will provide very good NOx output. Because of its small size, that means the whole combustor must have large number of modules. In this case, fuel air modules arrangement on dome and their installation on combustor must have good design.

4.3 Direct mixing fuel air module design

The direct mixing fuel air module for high pressure low emissions combustor is shown in **Figure 9** [11]. The design is very simple. At the inlet there is an axial swirler of low swirling strength, geometrical swirling angle is 35 degree, with thin swirler curved blade of thickness 0.045 in. It is suggested using 0.88 for swirler discharge efficient. In the center there is a simple pressure swirl fuel nozzle. The module has a convergent section of half angle 45 degree at exit. The fuel nozzle exit surface is at the throat section (0.02 in) downstream side. There is a very short divergent section of half angle 75 degree. It is not for aerodynamics, such as a "swirl-venturi". It is for a structural purpose, in the module floating design. The module exit has a cross sectional area ACd smaller than the inlet ACd. That makes the exit a metering device.

4.4 Arrangement of fuel air modules on dome

The arrangement of large number fuel air modules on dome is shown in **Figure 10**. All fuel nozzles are of same size, all air-alone modules are aerodynamically the same and all the same size. Air-alone modules are staying on dome, only

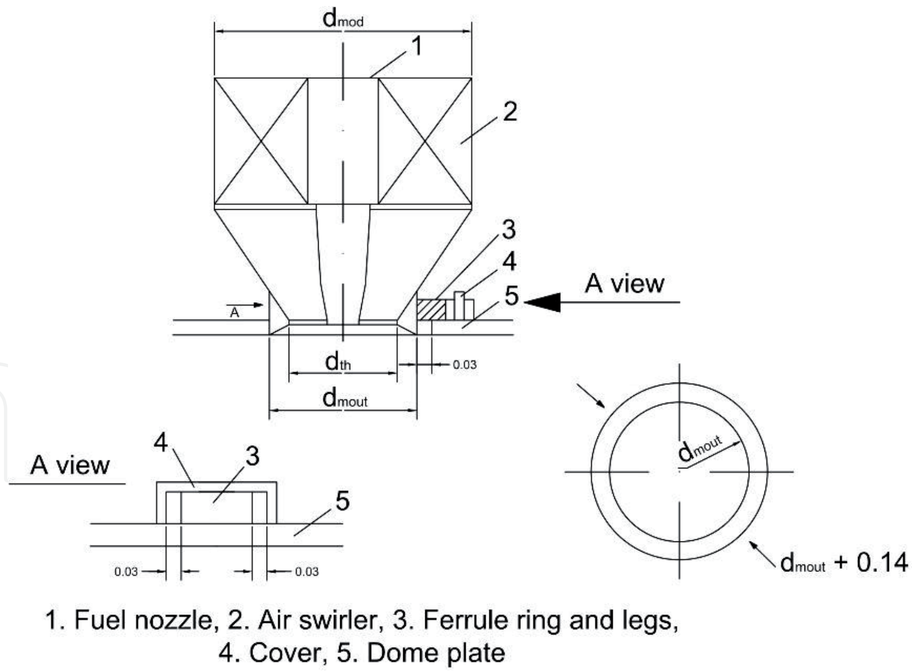

Figure 9.
Fuel-air module [11].

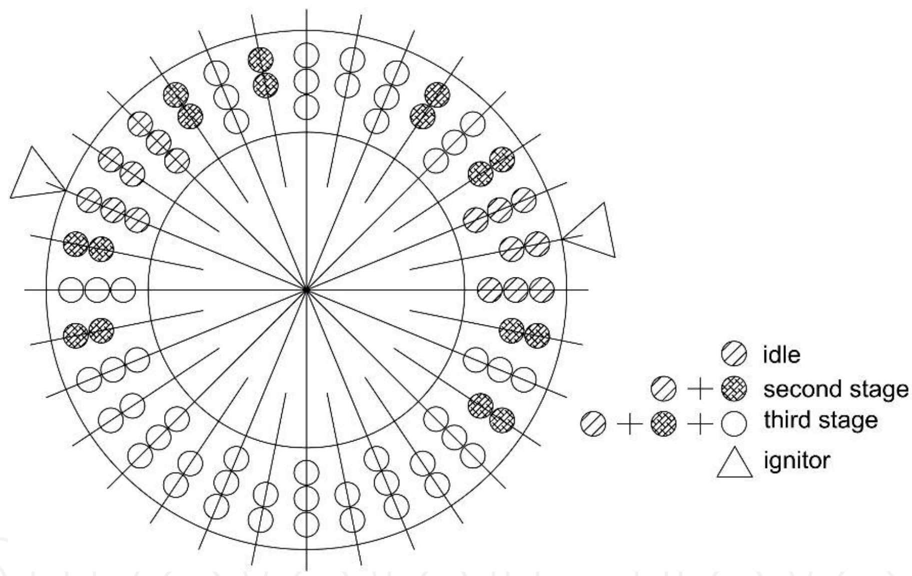

Figure 10.
On dome fuel-air module arrangement [11].

fuel nozzles are installed from air casing. This design idea is from the GE LM 6000 industrial low emissions combustor [12]. In the LM 6000, there are large number of premixed fuel (natural gas) and air modules. As they are premixed modules, the size is big, thus the opening on air casing is rather large. For the present design, the module is not premixed, only fuel nozzle is passing through air casing, the opening can be much smaller.

In **Figure 10**, altogether there are 80 fuel air modules. Distributed in three rows. From outer liner towards inner liner, they are 32, 32, 16 modules. The whole combustor is having three stages, as shown in **Figure 10**, first stage is idle condition, 16 modules are working. Second stage is from 20% power condition to 50% power condition, 32 modules working. Third stage is from 50% power condition to 100% power condition, all modules are working.

4.5 Installation of fuel nozzles on dome

Fuel nozzles are not installed individually. They are installed in cluster nozzles. There are two types of cluster nozzle. One is three fuel nozzles in one cluster, the other is two fuel nozzles in one cluster. Because the fuel nozzles in one cluster are all in the same stage, so inside the cluster stem there is only one fuel line. That will simplify the cluster nozzle. The cluster of three fuel nozzles is shown in **Figure 11**. From liner axial direction, the cluster is close to one fuel nozzle size. The opening on air casing is not big, as shown in **Figure 12**, it is only an ellipse of one inch times two inches, much smaller than the opening on LM 6000 air casing. It is because of two reasons: first, in this design only the fuel nozzle passes through the air casing. The air-alone module does not pass through the air casing. In the LM 6000, fuel injector and air module together pass through the air casing. Second, in this design in one cluster, nozzles are all in the same stage, that makes cluster simplified and reduces the size. During installation, in one three nozzle cluster, three nozzles shall be installed onto dome to match three air module center holes, that requires very accurate manufacturing and accurate assembly. The same situation for two nozzle cluster installation. This is the reason as shown in **Figure 9**, there is a floating design. It allows the air-alone module moving in either direction 0.03 in. In this design, only the middle row air-alone modules are welded with dome without floating design, other air modules are all with floating design to make the assembly easier.

4.6 Air distribution and liner cross sectional area

For a high pressure low emissions combustor, its air flow distribution is combustion air 75% and cooling air 25%. The liner layout has no primary air holes, no dilution air holes. Liner cross sectional area is designed by 12 times combustion air ACd, or it can also be designed as liner average Mach number 0.02. The Mach number is defined by that, air flow rate is combustion air, sonic velocity is defined by inlet air temperature, air density is defined by inlet air pressure, inlet air temperature.

Notice the design choices will always need several times modification, make good balance between the following items:

- Liner average diameter (affect total number of modules and the circumferential spacing between modules)
- Liner annular height (affect module radial spacing)
- Module detailed design (affect module inlet diameter and module exit diameter)
- For module installation, the required minimum floating distance (may affect the locations of modules with floating design)

The key item is the total number of fuel air modules. That will affect the ACd for each air module and module size, also affect fuel nozzle flow number and whole fuel air module arrangement on dome.

4.7 Fuel nozzle design

Fuel nozzle is designed for the maximum condition. At the 100% condition, the nozzle injection pressure drop is between 400 psig and 800 psig. At the idle

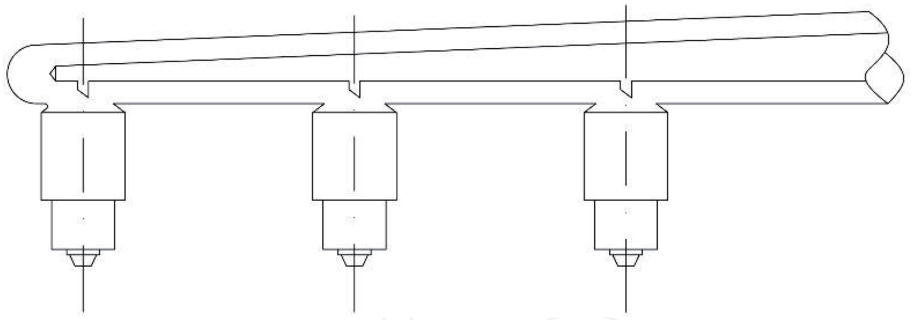

Figure 11.
Cluster of 3 nozzles [11].

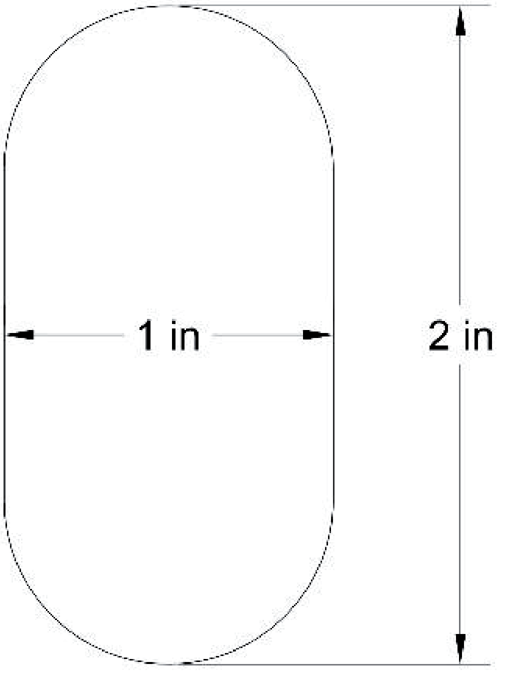

Figure 12.
Opening on air casing for cluster fuel nozzles [11].

condition, fuel nozzle pressure drop is 120 psig. At all operational conditions, such as before one new stage is opened, nozzle pressure drop shall not be higher than 800 psig and just after a new stage is opened, nozzle pressure drop is not less than 100 psig.

Since it is for a high pressure low emissions combustor, there needs to be a fuel pump with very high pressure capacity.

The control of fuel staging is simple on-off valve.

4.8 90-degree sector combustor design

90 degree sector combustor design is shown in **Figure 13**, which is a rectangular shape, not a fan shape. Previously a 90 degree sector was usually cut from a full annular combustor, the cost was a whole full annular combustor. And the traversing gear to measure exit temperature distribution is complicated. From present author's experience, using a rectangular 90 degree sector will not affect the combustor development, its aerodynamics will not be affected. Two side walls are water cooled with no effect on air distribution. The combustion data will be taken from the middle 60 degree sector. The rectangular 90 degree sector design idea is taken from reference [13]. In reference [13], the recommended 90 degree rectangular sector is shown in **Figure 14**, which was designed by the present author.

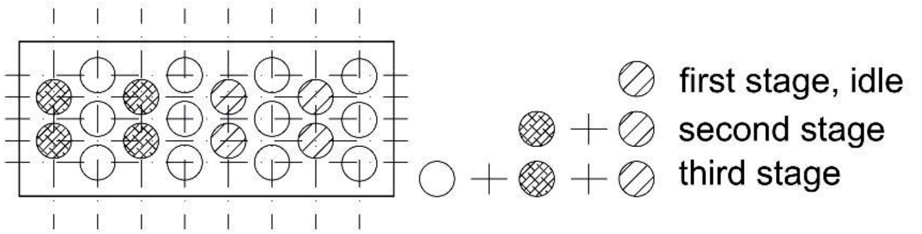

Figure 13.
Sector combustor of 20 fuel-air modules.

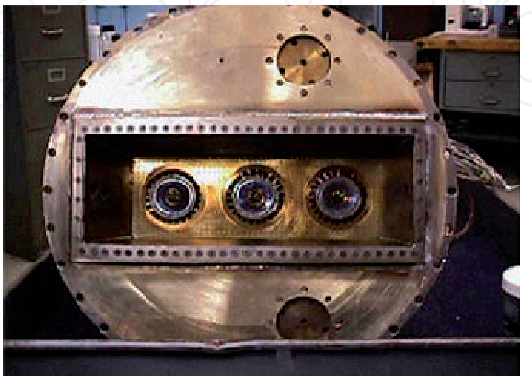

Figure 14.
Sector test combustor (shown with 3 fuel injectors) [13].

5. Combustor performances

This high pressure low emissions combustor design has good combustion performances. First, the high power condition EI NOx is good, which is very close to a well-developed LPP system. The high pressure EI NOx can be easily obtained by single module tubular combustor test.

High altitude ignition is good, because as shown in **Figure 10**, the fuel nozzle spray for ignition is rather close to ignitor and there is no other air in-between spray and ignitor.

Flame stabilization is good. Idle LBO is good for two reasons:

- The combustion equivalence ratio for working fuel air module is 1.2
- As shown in **Figure 10**, at idle condition there are 8 modules working as a group in one combustion zone. There is not much non-working module air quenching effect. Particularly there are two working module flames which are protected by the surrounding flames. They support each other, make the idle LBO a very good one.

For the 30% power condition, as the designed working modules combustion equivalence ratio is close to one, which is good flame stabilization for the storm weather heavy rain test.

As it is non-premixed, lean direct mixing combustion with low swirling, there will not be severe combustion instability.

For exit temperature distribution, the pattern factor is low. Because there is small scale mixing, it is close to uniform heat release combustion.

For the exit radial profile, this design has its natural feature for good radial profile. If there needs some minor adjustment, the designer may easily move the two fuel nozzle cluster and related air modules radially just a little bit.

One additional advantage for this combustor design is that, for high pressure low emissions combustor development, very often there is a lack of such a high pressure and high air flow rate test facility to run up to the 100% power condition. When there are such facilities, the running cost is very high. For this combustor design, only 1.25% of 100% power condition air flow is required for single module tubular combustor test. That is, the designer can run a large number of tests to verify the effect of pressure, air temperature, FAR on EI NOx to correlate an equation of

$$\text{EI NOx} = f\ (P,\ T,\ \text{FAR}) \tag{1}$$

That gives the designer opportunity to study the combustion in depth.

6. Summary of this chapter

- The new generation civil aero combustor is a high pressure (such as 70 atm) low emissions combustor. The new generation military aero combustor is a high FAR (such as 0.051) combustor. For combustion organization, they are both direct mixing combustion. For the civil combustor, it is a lean direct mixing combustion concept. For the military combustor, it is a stoichiometric direct mixing combustion concept. They both require a high combustion air fraction, such as 75%. The liner will have no primary holes, no dilution holes. Cooling air is reduced to 25%. There must be advanced cooling technology. The liner design for the new generation aero combustor has been reported in this chapter. New generation aero combustor also needs some more technology development.

- As 75% air coming into liner through dome, there needs to be a new inlet diffuser design. The new diffuser design for the new generation aero combustor will be reported somewhere else by the present author

- The new generation aero combustor needs a new liner material, which is ceramic matrix composites (CMC). Such technology is available. For further development, two problems need to be solved. One is how to drill tiny small cooling holes on CMC. The other is how to connect CMC with metal parts. For the second problem, there needs a transition region, from metal gradually change to CMC, then CMC part can easily weld or connect to metal parts

- The new generation aero combustor will require to be fabricated with additive manufacturing (or 3-D printing manufacturing). Such technology is available. It needs further development to be used for liner dome parts, in addition to fuel nozzles, currently made by such technology

- New generation aero combustor shall have laser ignition technology. This technology is not available now. It will be particularly useful for high altitude ignition. Such technology shall be developed in the future.

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